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Jian Li

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University of Florida
Office of Engineering Research
343 Weil Hall, P.O.Box 116550
Gainesville, FL 32611

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14. ABSTRACT
Continuous active sonar (CAS) in the presence of strong direct blast is studied for the Doppler-tolerant linear frequency modulation waveform. A receiver design which is capable of detecting slowly moving, stationary, or tangentially moving targets, while simultaneously providing low false alarm rate is developed. This receiver uses an adpative beamformer to suppress the direct blast signal to a managable level, so that effective target detection with acceptable false alarm performance is achieved. In fact, the developed receiver is capable of detecting the target signal without false alarms caused by the direct blast using only a single-ping of received data. The performance of the system with either a DAS beamformer, or one of three Capon beamformer variants is examined.

15. SUBJECT TERMS
Pulsed active sonar (PAS) , continuous active sonar (CAS), strong delay and Doppler-spread direct blast, Doppler-tolerant linear frequency modulation waveform, Doppler-sensitive SHAPE waveform, in-water experimentation results.

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Enhanced Multistatic Active Sonar via Innovative Signal Processing

Jian Li

Department of Electrical and Computer Engineering, P.O. Box 116130
University of Florida, Gainesville, FL 32611
phone: (352) 392-2642   fax: (352) 392-0044   email: li@dsp.ufl.edu

LONG-TERM GOALS

Our goal is to address fundamental signal processing research issues for enhanced multistatic active sonar systems. To effectively mitigate the reverberation problems and direct blasts encountered in shallow water, both probing waveform synthesis and adaptive receive filter design techniques should be investigated. To efficiently and accurately estimate the target positions and velocities, both target association schemes and weighted target parameter estimation methods should be devised.

OBJECTIVES

Our objectives of the current effort are to (1) develop a set of structured algorithmic approaches for both pulsed active sonar (PAS) and continuous active sonar (CAS) systems for range-Doppler and range-compression processing, and (2) to provide TREX13 in-water experimentation results aimed at highlighting the merits and limitations of PAS and CAS, as well as Doppler-tolerant and Doppler-sensitive waveforms in the presence of a strong delay and Doppler-spread direct blast.

APPROACH

Active sonar systems can have a variety of configurations namely mono-static, bi-static and multi-static. This report deals with a dataset generated from an in-water experiment where a bi-static scenario was established. Active sonar systems are further classified on the basis of the type of waveform they utilize to illuminate the region of interest. They include PAS and CAS. PAS systems work on the principle of broadcasting a low duty cycle high instantaneous power pulse into the region of interest followed by a long listening time, while the CAS systems broadcast a waveform that is characterized by a high duty cycle and low instantaneous power. PAS systems due to their high instantaneous power may have a detrimental effect on the marine life, while the CAS systems do not pose such dangers due to their low instantaneous power. CAS systems are also attractive from the point of view of having continuous access to the target, as the target is illuminated by the pulse for nearly the complete pulse repetition interval (PRI), and hence opening up the avenue for better target tracking than its PAS counterpart. In this report both the PAS and CAS systems are studied first for a particular set of probing waveforms and then the CAS system, due to its stated benefits, is investigated further.

The key individuals participating in this work include the PI, Dr. Jian Li, her Ph.D. students, Mr. Akshay Jain, Mr. Shujian Yu, Mr. Christopher Gianelli, and the Adjunct Research Assistant Professor, Dr. Luzhou Xu, all of the University of Florida.

WORK COMPLETED

As mentioned in the previous year's report, the receiver design is of paramount importance in active sonar system performance. For a pulse compression active sonar system equipped with an array of transducers both spatial and temporal receiver design must be considered. The well-known delay-and-sum (DAS), or spatial matched filter (MF), and temporal MF may not provide satisfactory performance in scenarios with multiple targets, strong reverberations, or interference. In such cases, alternate receiver designs which are either suited to a particular target, noise, clutter, and interference scenario, or designs which adapt to a changing target, noise, clutter, and interference scenario, should provide superior performance.

In CAS systems, the target return is often masked by the pulse compression sidelobes caused by the transmitter direct-path signal, or is much weaker than these sidelobes, yielding an unacceptable number of false alarms. This problem was previously addressed via a simple and effective generalized likelihood ratio (GLR) criteria that enhanced the range Doppler/range compression images generated via processing the received pulses with a spatial and temporal MF. While yielding excellent target detection and false alarm performance, this receiver and detector design requires the accumulation of many pings, dramatically increasing the time prior to declaring a detection. Further, this approach relies on the target's radial motion, limiting the effectiveness of the receiver against stationary, slowly moving, or tangentially manuevering targets.

In this report, a receiver design which is capable of detecting slowly moving, stationary, or tangentially moving targets, while simulatenously providing low false alarm rate is developed. This receiver uses an adpative beamformer to suppress the direct blast signal to a managable level, so that effective target detection with acceptable false alarm performance is achieved. In fact, the developed receiver is capable of detecting the target signal without false alarms caused by the direct blast using only a single-ping of received data. The performance of the system with either a DAS beamformer, or one of three Capon beamformer variants is examined.

RESULTS

From the TREX13 data, the Doppler-tolerant LFM waveform is used to evaluate the performance of the receiver design. The focus is on the CAS LFM collection, which has an 18 second waveform, and 20 second pulse repetition interval (PRI). Thus, the CAS LFM system has a 90% duty cycle. The key to achieving reliable detections with acceptable false alarms rate with a single-ping of data is to suppress the direct blast signal via beamforming. Due to the non-stationarity of the ocean environment, as well as the large amount of angular spread experienced by the transmitter-to-receiver direct path signal, a beamformer which places a fixed null at the angle of the transmitter is not effective. Indeed, ping-to-ping adaptivity is required to achieve consistent direct path signal suppresssion.

Range versus slow-time images for a beam pointed at the outbound target for the CAS-LFM system are illustrated in Figs. 1(a)-(d). The beamforming algorithm used to generate the data for Figs. 1(a)-(d) are the DAS, Capon, diagonally loaded Capon (Capon-DL), and generalized linear combiner robust Capon beamformer (GLC-RCB), respectively. Despite the fact that the LFM signal is Doppler tolerant,

the extreme length of the probing sequence in CAS collections allows for non-negligible gain in temporal matched filter processing by matching the received signal in both delay and Doppler. Thus, the images in Fig. 1(a)-(d) are formed by taking the maximum value over Doppler space for each PRI and range bin shown in the image. Fig. 1(a), which displays the DAS beamforming result, highlights the challenge of achieving acceptable false alarm rates in CAS systems. Note that all the images in Fig. 1 have been normalized such that the peak value in the image has a value of 0 dB. Inspecting this image, it can be seen that the direct blast signal dominates the target return in each PRI, which will lead to a great deal of false alarms. To suppress the direct blast signal, the well-known Capon beamformer is applied, and the result is displayed in Fig. 1(b). Examining this image, it becomes clear that the Capon beamformer is achieving a good deal of direct blast suppression. This can be seen by comparing the relative strength between the direct blast region, and the background power. In the DAS image of Fig. 1(a), the direct blast is much stronger than the background power, whereas in the Capon image the direct blast signal is much closer in power to the background level. Inspecting the target signature in Fig. 1(b), it is also clear that the contrast between the target and its immediate surroundings has been reduced. Thus, the Capon beamformer may not provide an ideal trade between direct blast suppression and target signal enhancement. To remedy this problem, the Capon-DL approach is applied, which offers a user-parameter, the amount of diagonal loading, to trade between direct blast suppression and target signal enhancement. The image generated by applying the Capon-DL is displayed in Fig. 1(c). Clearly, the Capon-DL provides a moderate amount of direct blast suppression, as shown by comparing the power of the direct blast signal to the nominal background level. Further, the contrast between the target signal and its immediate surroundings has been increased from the Capon beamformer. One challenge in using a Capon-DL is selection of the diagonal loading level. This parameter may need to be varied from ping to ping, which may cause the performance of the beamformer to fluctuate. The GLC-RCB beamformer is related to the Capon-DL beamformer, but the diagonal loading level is set automatically, and is computed as a function of the received data. The result generated from the GLC-RCB beamformer is displayed in Fig. 1(d). Comparing the GLC-RCB result with the Capon-DL image, it can be seen that while the Capon-DL approach offers more direct blast suppression, the GLC-RCB algorithm has superior contrast between the target and its immediate surroundings. The increased contrast between the target signal and the surroundings implies that the target should be well-detected.

The target detection processing for the imagery in Figs. 1(a)-(d) involves normalizing the data in fast-time via a sliding window approach. This processing highlights targets or range bins which are stronger than their immediate neighbors. It should be noted that the target detection is carried out using only a single ping of received data. Figs. 2(a)-(d) display the PRI vs. range images after fast-time normalization for the DAS, Capon, Capon-DL, and GLC-RCB algorithms, respectively. As expected, the DAS beamformers offers no direct blast suppression, which in turn yields a fast-time normalized image where the direct blast signal dominates each PRI. As indicated by the results in Fig. 1(b), the Capon beamformer, displayed in Fig. 2(b), achieved a great deal of direct blast suppression, but also reduced the contrast of the target signal. Thus, while false alarms casued by the direct transmitter-to-receiver path are unlikely, false alarms caused by the high background energy are a concern. The Capon-DL result, shown in Fig. 2(c), appears to provide a reasonable trade between direct blast suppression and target contrast. Comparing the Capon-DL result to the GLC-RCB image in Fig. 2(d), it is seen that the images are similar. While the direct blast has a more faint appearance in the Capon-DL approach, the GLC-RCB has superior target area contrast.

After the fast-time normalization processing highlights targets or range bins which are stronger than their immediate neighbors, the fast-time normalized imagery is thresholded, and pixels which exceed

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the threshold are considered potential targets. Figs. 3(a)-(d) display the pixels which are greater than 20 dB above their immediate neighbors, as computed by the fast-time normalization processing, for the DAS, Capon, Capon-DL, and GLC-RCB beamformers, respectively. Inspecting Fig. 3(a), it is clear that the DAS beamformer will not offer reasonable false alarm performance, due to the strong direct blast presence in each PRI. It also bears noting that the DAS algorithm does provides a good detection probability, due to the fact that the target signal power is maximized via this processing. The Capon beamformer result, displayed in Fig. 3(b) demonstrates why a balance must be struck between direct blast suppression and target signal enhancement. Due to the loss of contrast between the target and its immediate surroundings, the Capon beamformer is totally unable to detect the target at this threshold. This is essentially the converse of the DAS beamformer performance, which offered good detection rate, with very poor false alarm rates. Comparing the Capon-DL beamformer result shown in Fig. 3(c) to the previously considered DAS and Capon beamformers, it is possible to see a better balance between direct blast suppression and target signal contrast. Unfortunately, the challenge of selecting the "best" level of diagonal loading for the Capon-DL approach is still not always clear. The GLC-RCB image in Fig. 3(d) clearly offers the best trade between false alarm rate and correct detections, successfully combining some attributes of the DAS beamformer (target signal enhancement) and some attributes of the Capon beamformer (direct blast suppression). Furthermore, the diagonal loading level of the GLC-RCB algorithm is set automatically as a function of the data, providing good performance without requiring the tuning of a user-parameter.

IMPACT/APPLICATIONS

The littoral submarines are small, quiet, and non-nuclear, making active sonar an essential technology needed for their detection. Enhancing the multistatic active sonar network's capability through innovative waveform synthesis and receive filter design is critical to improving the Navy's ability to conduct anti-submarine warfare.

Given the inherent high duty cycle of CAS systems, and the requirement to obtain timely target detections, effective suppression of the direct blast signal on a ping-to-ping basis is a crucial feature for any receiver. In this context, effective suppression involves maintaining the target signal while rejecting the direct blast to an acceptable level. The proposed receiver design, with the GLC-RCB beamformer, allows for reliable single-ping detection of targets regardless of their motion.

Furthermore, direct blast suppression via adaptive beamforming may lead to sucessful use of novel waveforms such as the CAS-SHAPE sequence for multistatic CAS networks. Indeed, after suppressing the strong, constant direct blast signal spatially, conventional range-Doppler processing may offer good performance with the SHAPE waveform. Unfortunately, the algorithms developed for the CAS-LFM system have not shown good performance with the SHAPE waveform at this time. However, with the principle of achieving an excellent tradeoff between direct blast suppression and target signal enhancement demonstrated, it is a matter of identifying or developing an adaptive beamforming approach that works with the SHAPE waveform. This would represent a great accomplishment, as the SHAPE waveform offers unbiased and accurate range and velocity estimates, as well as covertness when compared with the standard LFM signal.
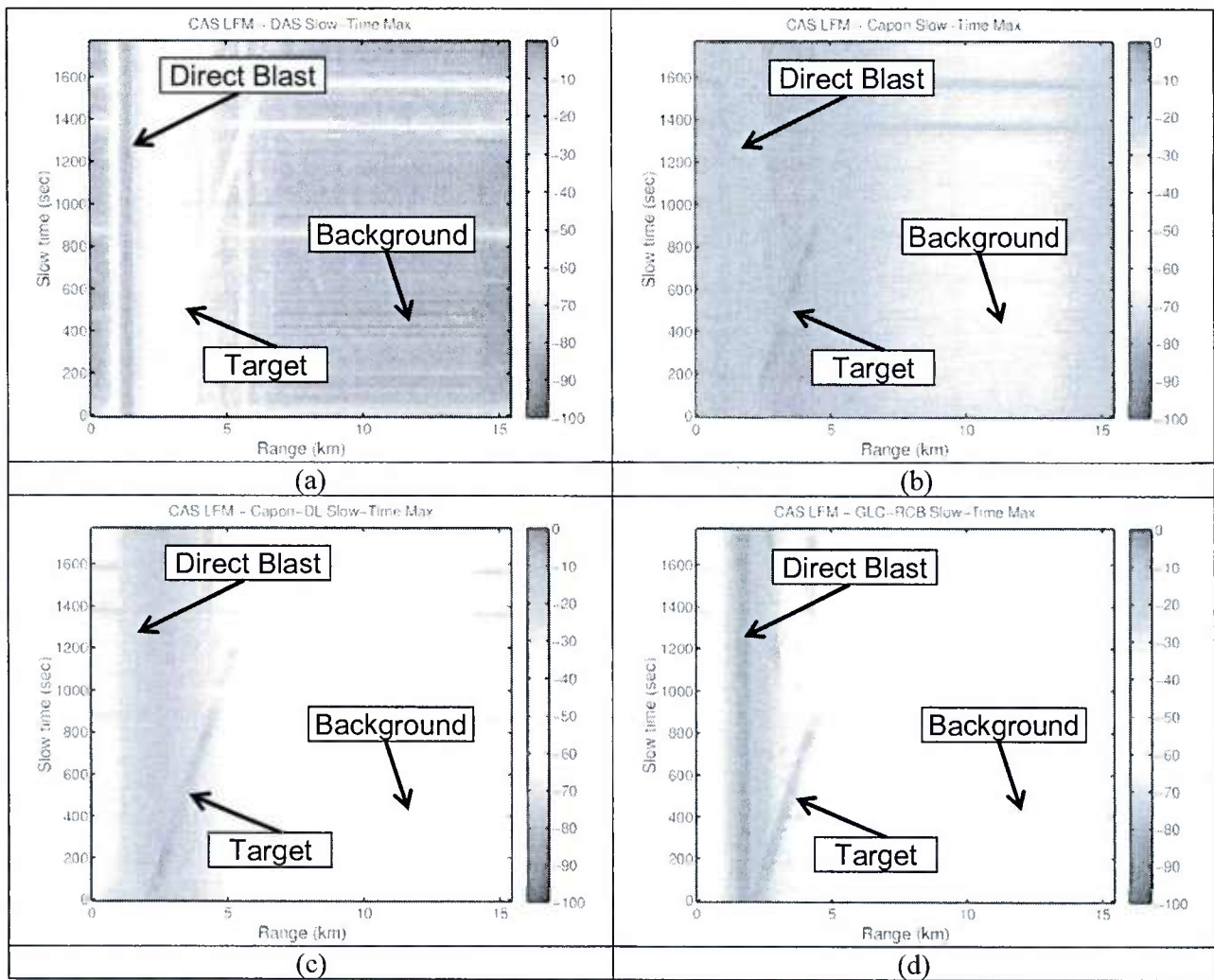
Figure 1. (a) PRI vs. range image for CAS-LFM with DAS beamforming. (b) PRI vs. range image for CAS-LFM with Capon beamforming. (c) PRI vs. range image for CAS-LFM with DL-Capon beamforming. (d) PRI vs. range image for CAS-LFM with GLC-RCB beamforming.

[graph: GLC-RCB beamforming provides a superior tradeoff between direct blast suppression and target signal enhancement.]
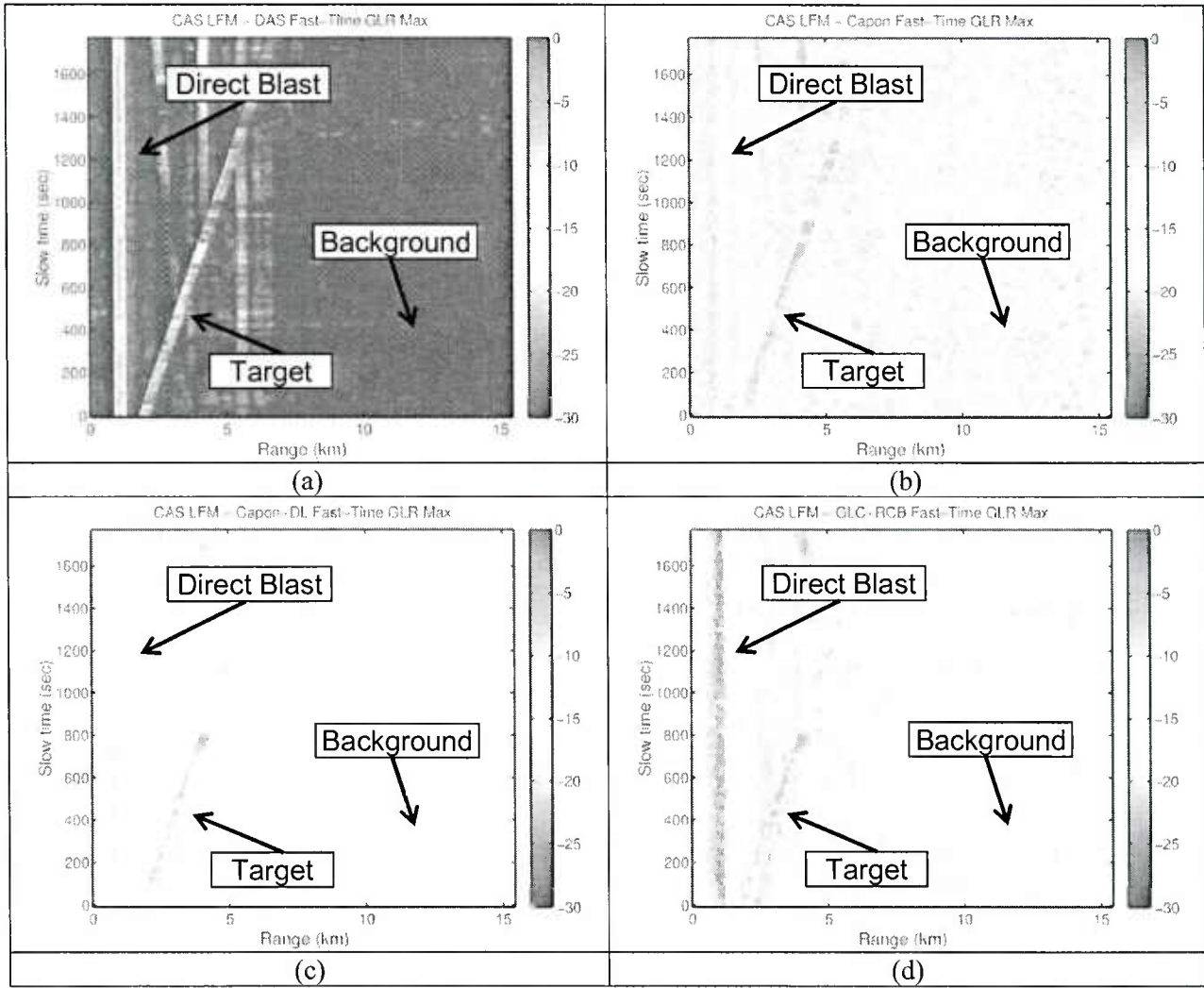
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Figure 2. (a) PRI vs. range image for CAS-LFM with DAS beamforming after fast-time normalization. (b) PRI vs. range image for CAS-LFM with Capon beamforming after fast-time normalization. (c) PRI vs. range image for CAS-LFM with DL-Capon beamforming after fast-time normalization. (d) PRI vs. range image for CAS-LFM with GLC-RCB beamforming after fast-time normalization.

[graph: Effect of fast-time normalization on PRI vs. range imagery for various beamformers.]
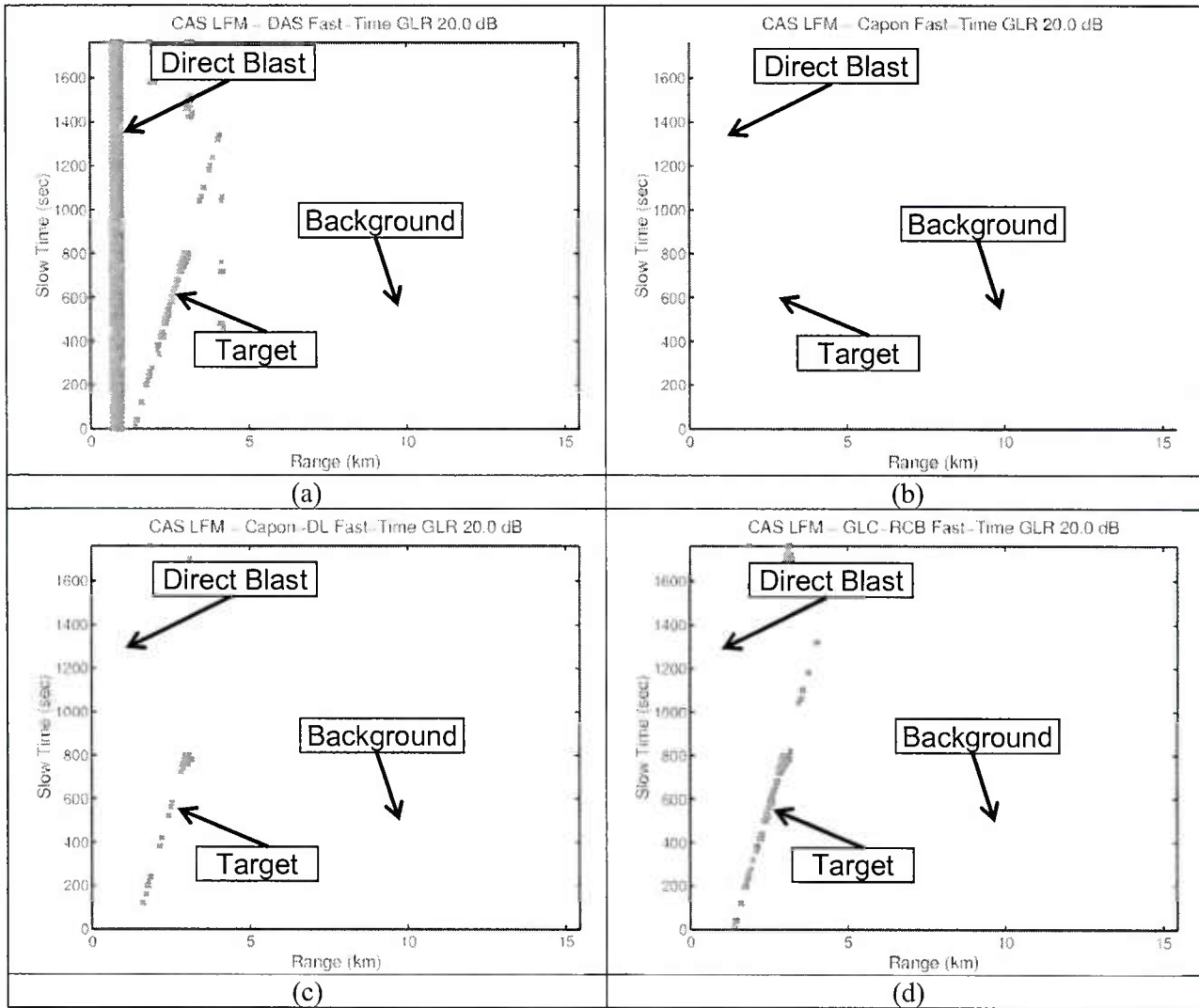
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Figure 3. (a) Thresholded DAS beamformer image. (b) Thresholded Capon beamformer image. (c) Thresholded Capon-DL beamformer image. (d) Thresholded GLC-RCB beamformer image.

[graph: The superior tradeoff between direct blast suppression and target enhancement offered by GLC-RCB provides best trade between detection performance and false alarm rate.]

TRANSITIONS

We have provided several CAN sequences to Dr. Michael S. Datum of the Applied Physical Sciences Corporation. He has used some of the sequences as active sonar probing sequences and generated simulated datasets for ASW scenarios using the sonar simulation toolset (SST). He has also used the sequences for in-water experimentations.

We have participated the TREX-CAS in-water experimentation in 2013. We have gained much experience and insights analyzing the experimental data collected during the experimentation. Dr. Paul Hines of Defence R&D Canada apparently likes our results very much and told us that *"You are the best!"*

We have sent our probing waveform synthesis papers to Dr. James Alsup (alsup@cox.net) and our IAA papers to Dr. Roy Streit (streit@metsci.com).

We have also sent our presentation slides for the 2013 IEEE Underwater Acoustic Signal Processing Workshop to Dr. Don Russo (donato.russo@navy.mil) of Naval Air Warfare Center and Dr. Michael Janik (Michael_F_Janik@raytheon.com) of Raytheon Integrated Defense Systems.

RELATED PROJECTS

NONE.

PUBLICATIONS

Book

H. He, J. Li, and P. Stoica, *Waveform Design for Active Sensing Systems -- A computational approach*, Cambridge University Press, 2012. [published, refereed].

Journal Publications

K. Zhao, J. Liang, J. Karlsson, and J. Li, "Enhanced Multistatic Active Sonar Signal Processing," *The Journal of the Acoustical Society of America,* Vol. 134, No. 1, pp. 300-311, July 2013. [published, refereed].

L. Xu, K. Zhao, J. Li, and P. Stoica, "Wideband Source Localization Using Sparse Learning via Iterative Minimization," *Signal Processing*, Vol. 93, No. 12, pp. 3504-3514, December 2013. [published, refereed].

J. Ling, L. Xu, and J. Li, "Adaptive Range-Doppler Imaging and Target Parameter Estimation in Multistatic Active Sonar Systems," *IEEE Journal of Oceanic Engineering,* Vol. 39, No. 2, pp.

290-302, April 2014. [published, refereed].

W. Rowe, P. Stoica, and J. Li, "Spectrally Constrained Waveform Design," *IEEE Signal Processing Magazine*, Vol. 31, No. 3, pp. 157-162, May 2014. [published, refereed].

J. Liang, L. Xu, J. Li, and P. Stoica, "On Designing the Transmission and Reception of Multistatic Continuous Active Sonar Systems," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 50, No. 1, pp. 285-299, May 2014. [published, refereed].

L. Xu, J. Li, and A. Jain, "Impact of Strong Direct Blast on Active Sonar Systems," *IEEE Transactions on Aerospace and Electronic Systems*, Vo. 51, No. 2, pp. 894 – 909. [published, refereed].

Conference Publications

K. Zhao, J. Liang, J. Karlsson, and J. Li, "Enhanced Multistatic Active Sonar Signal Processing," *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Vancouver, Canada, May 26-31, 2013. [published, refereed].

J. Li, "On Designing the Transmission and Reception of Multistatic Continuous Active Sonar Systems," *2013 IEEE Underwater Acoustic Signal Processing Workshop*, West Greenwich, Rhode Island, October 16-18, 2013. [invited]

W. Rowe, J. Li, and P. Stoica, "Spectrally Constrained Waveform Design for MIMO Systems," *IEEE International Microwave Symposium*, Tampa Bay, FL, June 2014. [invited]

L. Xu, J. Li, and A. Jain, "Active Sonar Transmission Strategies in the Presence of Strong Direct Blast", 48th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, November, 2014. [in press, refereed].

C. Gianelli, L. Xu, and J. Li, "Active Sonar Systems in the Presence of Strong Direct Blast", *Oceans 2015*, Genoa, Italy, May 18-21.

HONORS/AWARDS/PRIZES

Dr. Jian Li gave a plenary talk at the IEEE Sensor Array and Multichannel Signal Processing Workshop, in Hoboken NJ, in June 2012.

Dr. Jian Li is a co-author of the following paper that received the 2013 IEEE Signal Processing Society Best Paper Award:

Amir Beck, Petre Stoica and Jian Li, "Exact and Approximate Solutions of Source Localization Problems," *IEEE Transactions on Signal Processing*, Volume: 56, No. 5, May 2008.
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4472183